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Technical Report

POTENTIAL OF GROUND EFFECT MACHINES

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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POTENTIAL OF GROUND EFFECT MACHINES

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Type C Final Report

by

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ABSTRACT

Ground effect machines appear to have some promise in high-speed operations. Since they do not operate in contact with the ground, they can cross terrain that would be impassable to more conventional means of locomotion.

This study considers the use of ground effect machines in three areas within the field of responsibility of the Bureau of Yards and Docks. These areas are: amphibious support, polar operations, and construction equipment. Each of these problem areas share a common major requirement, namely, the ability to move across mixed or unstable terrain with practical speed and load capacities.

It is concluded that ground effect machines have only limited application in the problem areas. The increase in mobility and operating speed can only be accomplished with large vehicles having very high rates of fuel consumption. On the basis of predicted performance, GEMS appear to be limited to carrying high-priority cargo. The noise and debris resulting from the air blast of the plenum chamber and peripheral jet are serious handicaps.

Qualified requesters may obtain copies of this report from ASTIA.
The Laboratory invites comment on this report, particularly on the
results obtained by those who have applied the information.

CONTENTS

INTRODUCTION

When an airfoil is moving close to the ground, the ground may cause a pronounced change in the aerodynamic forces acting on the airfoil.[1,2] Failure to recognize the lift on an airfoil moving at high speed in contact with the ground or water has had some disastrous effects on boats and cars attempting speed records. These effects have varied from a lack of high-speed control to actual ground looping of the vehicle.

A. Klemin[3] and E. A. Slatker,[4] writing in the "Journal of Aeronautical Science" in 1934, suggested, respectively, a moving belt and a reflection plate method of representing the ground when conducting wind tunnel tests.

Scattered attempts were made to apply the ground effect beneficially to support vehicles, or to reduce drag.[5] Those attempts included work by T. Kaario of Finland; C. Weiland of Switzerland; C. S. Cockerell of England; and J. C. M. Frost of Canada. In 1957, a report by the National Advisory Committee for Aeronautics, "Exploratory Study of Ground Effects on Thrust of Annular and Circular Nozzles" by U. H. Von Glahn,[6] gave impetus to the present extensive efforts in the United States. Work is being done to perfect vehicles that are supported wholly or in part by the ground effect, or as it is sometimes called "air cushion." These ground effect machines (GEMS) offer the promise of high-speed operation. Also, because they do not operate in contact with the ground, they can cross terrain that would be impassable to more conventional means of locomotion.

To be of value, ground effect machines must accomplish a necessary operation that has heretofore been impossible, or they must perform an operation more efficiently than methods now available.

The Bureau of Yards and Docks is responsible for the design, construction and maintenance of the Navy's shore bases, and the equipment used to accomplish these tasks. Ground effect machines will be considered for use in three problem areas within this responsibility: amphibious support, polar operations, and construction equipment.

Logistics has always been one of the main problems in amphibious operations. The requirement of operating rapidly enough to prevent a build-up of supplies on the beach has not always been met. Delays and confusion often result. Dispersion of forces to minimize damage from a single enemy action is an effective defense. With the advent of thermonuclear weapons, the requirement for dispersion is increased. A difficult operation is made more difficult, and the problem becomes one of transporting supporting supplies from a moving ship as much as 50 miles at sea to a point as much as 80 miles inland.

Vehicles can be effectively designed for use exclusively on firm ground, snow, or in water. However, at a given time, a polar region may include all of these and mud as well.

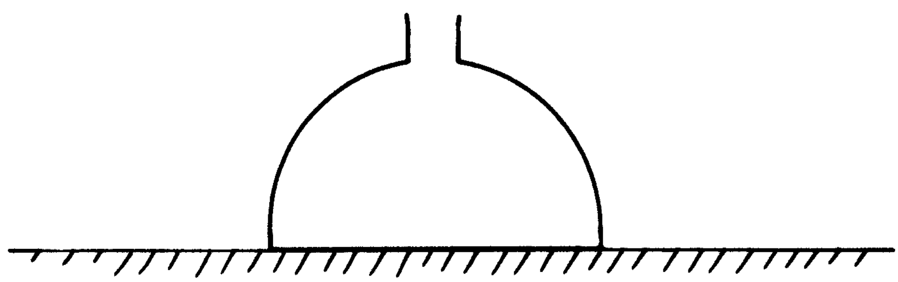
Construction of docking facilities on the shoreline will either be accomplished on rocky terrain, mud flats, or sand beaches. It might be said that construction in mud has often been solved the easy way — by not being undertaken. If construction must be done in a muddy region, it is usually necessary to wait until the mud dries. In marshes or mud flats it is often necessary to drain or fill the area before actual construction can be started.

These then are the problem areas. Although they are three different problems with three different methods, requirements, and objectives of operation, they share a common feature: the requirement of ability to move across mixed or unstable terrain with practical speed and load capacities.

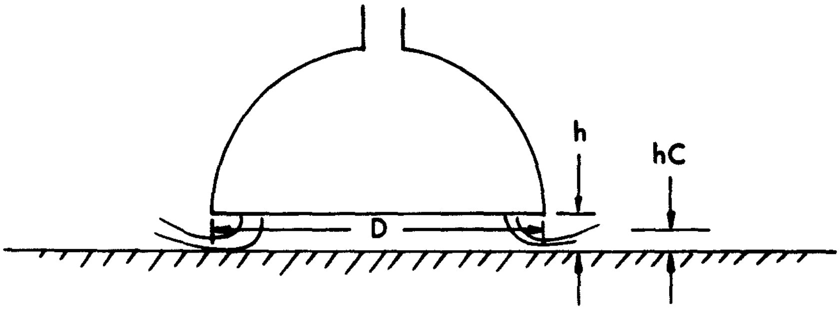
THEORY OF OPERATION

Although a great deal of work is being done to develop ground effect machines into practical and effective vehicles, an operating GEM can be of quite simple design.

Consider a hemispherical shell with an inlet duct at the pole. This would be classed as a plenum chamber. The shell rests on a rigid level surface so that the contact forms a relatively airtight seal.



Assume that a fan blows air into the shell. As the mass flow rate increases, the pressure within the chamber will increase until the product of the mean pressure and the projected area exceeds the weight of the shell. As this occurs the chamber will become airborne. Air will leak out on the periphery, but if the flow rate is maintained at a sufficient level, an equilibrium height is reached.



At equilibrium the lift is equal to the weight.

The hover height is determined by the flow rate ρAV. ρ is the mass of a cubic foot of air. In the basic theoretical study of plenum chambers, the air is usually considered to be incompressible, so that ρ is then the mass density of air at the prevailing atmospheric conditions. A is the effective area of discharge. Due to the vena contracta the discharge should be measured at some point beyond the perimeter where the restriction is the greatest. This is not practical, and the area of discharge at the perimeter is measured and adjusted by a discharge coefficient, C, a function of the Reynolds' number and the edge condition. For the circular chamber, consider that the discharge area is $hC\pi D$.

V_j is the exit velocity. This is determined by the internal pressure which is controlled by the weight that is carried.

The general horsepower requirement for hovering is

$$HP = \frac{hC\pi DV}{550}\left(\Delta P + \frac{MV_j^2}{2}\right)$$

In the above equation for a given set of conditions, the only improvement that can be made is in the discharge coefficient, C. The majority of the other types of ground effect machines have been developed to reduce the effective discharge coefficient.

PRESENT DESIGN CONCEPTS

Annular Jet[5]

If a small amount of power is used to discharge a high-velocity flow of air perpendicular to the ground on the periphery of the vehicle, this air curtain will greatly reduce the amount of power required to maintain a given hover height. By directing all of the air discharged inward from the periphery, some can be used to provide the lift while the remainder will serve as the air curtain.

Annular Jet With Skegs[5]

If the GEM is to operate exclusively over water, and at moderate speeds, a substantial power saving is effected by the use of side plates, or skegs, which extend into the water. The drag on the submerged portion of the skegs becomes very significant at higher speeds.

Water Curtain[5]

In principle, a ground cushion can be contained by a peripheral jet of water in just the same manner as a jet of air. If a thick jet of water is used, the piping system required and the water contained would weigh a staggering amount. Therefore, it is necessary to compromise in favor of a thin jet of water, but this provides an imperfect seal. Because of this imperfect seal, air must be pumped into the system at a substantial rate to maintain the cushion pressure.

Levapad[7]

The levapad operates successfully only at minute h:D ratios and has been compared with gas-lubricated bearings. Since it must operate on smooth surfaces, it would not be applicable to the problem areas defined in this report.

Labyrinth Seal[8]

In the labyrinth seal, air pressure is lowered in stages so that there is a minimum of loss into the atmosphere. Disadvantages that should be considered are the complexity of the mechanical design and a lack of knowledge of the effect of the ingestion of foreign matter.

Ram Wing[9]

The ram wing is not just a variation or improvement on the plenum chamber but is an entirely different concept. It depends for lift upon the compression build-up that occurs when an airfoil is moving in proximity with the ground. It is necessary for the vehicle to be moving at a high speed before this will occur. To obtain this speed the ram wing must be used in connection with either another ground effect or with conventional surface locomotion; therefore, its application is limited.

DESIGN CONSIDERATIONS

Some of the unconventional methods, or rather, the less commonly used or tried systems show considerable potential and continued effort is expected along these lines. However, the state of development of these concepts is such that it would be premature to include them here. In particular, the methods which are being referred to make use of viscous action for the sealing of the cushion such as in Weiland's labyrinth-seal or Hiller's diffuser-plenum.[10]

As has been concluded in the GEM Morphology study,[10]

> At the present state-of-the-art in GEM design and with the present level of information available on GEMS, it is almost impossible to precisely or analytically rate the various systems in order to arrive at the selection of the best type for a given application. Much more detailed and analytic evaluations would be warranted than has been undertaken in the present study to arrive at a more definitive selection of systems. This appears to be a fruitful field for investigation.

Although it is not necessarily the only suitable configuration, the annular jet is the one most thoroughly covered in the literature reviewed and most of the following considerations apply primarily to it.

Propulsion

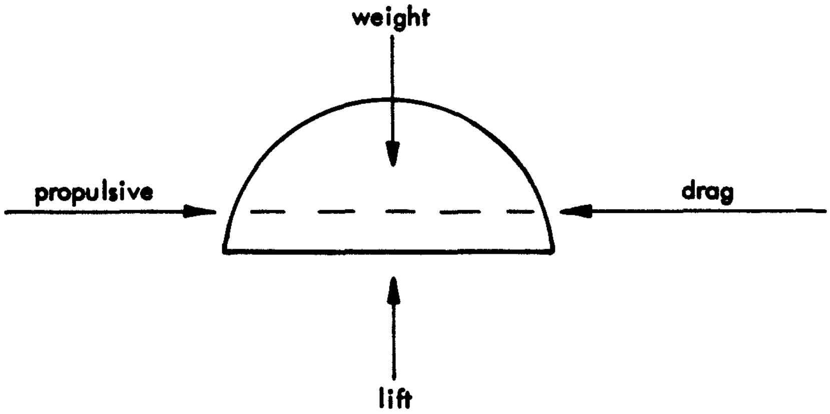
Because GEMS are not in direct contact with the ground, they depend upon the aerodynamic thrust of the propulsive system for forward motion, braking, and changes of direction.

Methods of propulsion fall into three categories: integrated, separate, and mixed.[10]

With integrated propulsion the air being discharged is directed so that the force produced is the resultant of a lift component and a propulsive component. Advantages are that for small angles from the vertical, the gain in propulsive force (which varies as the sine of the angle) is greater than the loss in lifting force (which varies as the cosine of the angle). With an annular jet configuration, louvers, vanes, or rotatable nozzles are used to deflect the jet. In the annular jet, deflections greater than 45 degrees with vanes are not practical. For greater jet deflections, rotatable nozzles should be considered.

An imbalance of forces to obtain a vehicle tilt would also provide a propulsive force from the air used to lift the vehicle. Kinetic means of obtaining control by a shift of body weight to tilt the vehicle is limited to small vehicles. Other means are available for providing tilt, but for low operating height the amount of tilt is limited. Also, the lift augmentation suffers with incidence angle, and the vehicle drag increases with increasing tilt.

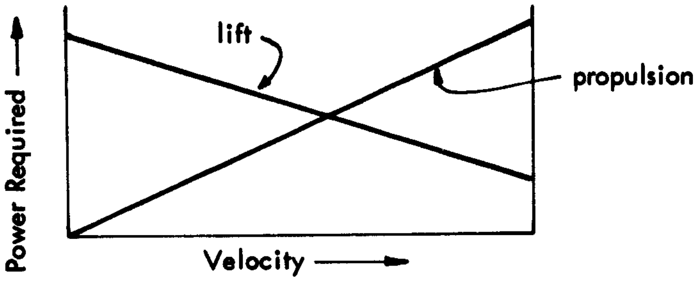
To avoid tilt it is necessary that the drag, propulsive force, weight, and lifting force are coincident.



There is a very definite theoretical and practical advantage in using an integrated propulsion system for the lower speed ranges.[10,11,12] To achieve the higher speeds a mixed or separate propulsion system must be used.

In a separate propulsion system, a propeller or ducted fan blows air in a plane parallel to the ground to provide the propulsion. A mixed propulsion system combines features of both the integrated and separate systems. To reduce the horsepower requirement it is necessary to arrange the drive train from the engine or engines so that any desired part of the shaft horsepower can be directed to either the lift or propulsion system.

The following diagram shows that at a constant operating height the power required for lift decreases with increasing speed. The sum of the lift and propulsion power is only slightly greater than the maximum of either.



The problem of control is well summarized by Cutler and Kossar:[13]

On the surface the control problem is fairly innocuous. At least it doesn't appear any more complicated than a low-speed aircraft. However, close examination reveals this problem has extremely difficult and unique facets. Consider the simple (?) problem of making a turn. Centrifugal force tries to throw you off the turn. The airplane banks into the turn, the car reacts the centrifugal force as a side load on the tires and the highway engineer is courteous enough to bank the roadway. What about the GEM? The height is too low to bank the machine and the zero friction with the surface precludes any reaction force from this quarter. The GEM must exert a side thrust proportional to velocity squared and inversely proportional to the turning radius. Exerting this force should not compromise the vehicle's clearance height.

Logically then, if the powerplant is not to increase, then forward thrust will be cut. The control system must then permit the operator to apportion the directional split of his thrust without compromising his clearance.

This requirement of delivering thrust simultaneously along two axes mutually perpendicular to each other also appears in the problem of holding track in a cross-wind. Quite obviously this may be done by crabbing, however, the physical surroundings may preclude this approach.

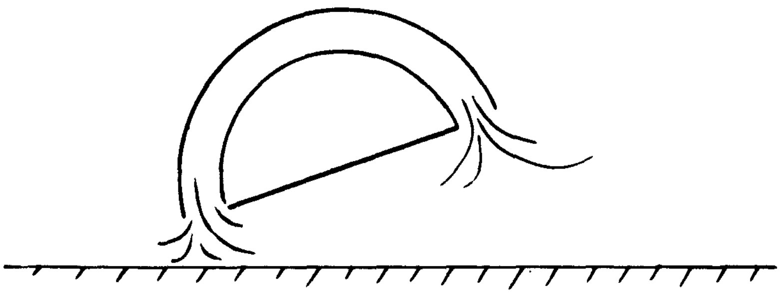
Another facet of the control problem is the deep seated desire to permit the GEM to be driven by personnel with the same skills as those required to drive conventional wheeled and tracked vehicles rather than skills associated with piloting aircraft.

Finally, the control system should not introduce undesirable perturbations into the system. This may come about as a result of venting a large portion of the air flow for control purposes thereby causing the vehicle to roll, pitch, or yaw about an axis where no motion is desired.

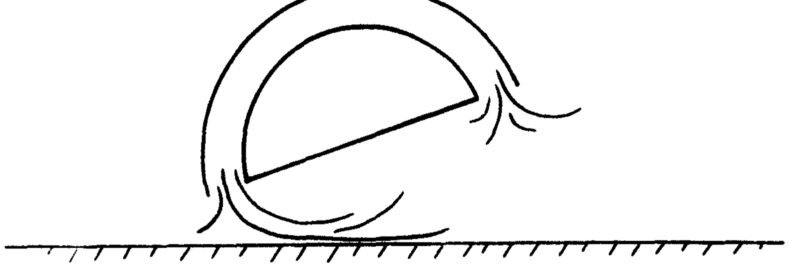
Directional control may be incorporated with the forward-speed control, turning being accomplished by providing more propulsive thrust on one side of the vehicle than on the other.[12] Alternately the propulsion engines may be pivoted so that they rotate in a horizontal plane. Whenever a vehicle uses the mixed or integrated propulsion system, it can be expected that the vanes or nozzles in the annular jet will also serve the purpose of control.[10]

Stability

One of the main problems that has been encountered with GEMS is that of stability, or the ability to return to the original position after a disturbance. It would appear that in the position shown for an annular jet the low side would exert a greater force due to the increased proximity to the ground and be self-restoring.



Extensive work has been done on both two- and three-dimensional models[14] and results show that this is not always true, and that as the angle of tilt increased, cross flow under the chamber caused a further increase in the angle of tilt.



The total reaction due to tilting is that caused by the shift of the base center of pressure and the jet reactions. In tests by Carmichael and Southcote,[14] the base exhibited a shift in center of pressure to the high side (divergent moment) for all conditions. The jet reactions provided an increment of center-of-pressure shift to the low side (convergent moment) at low angles of tilt. The jet-reaction shift was, however, in the divergent direction at high angles of tilt.

A three-dimensional model at h:D = 0.03 had a stable base-pressure distribution as opposed to an unstable one for the two-dimensional case. At h:D = 0.10 both models exhibit an unstable base-pressure distribution; however, it is less severe in the three-dimensional model.

> The only positive inherent stability which the simple annular jet possesses is altitude stability. If prevented from pitching or rolling, the simple annular jet at a fixed power setting has a strong tendency to seek a fixed altitude, and to return to that altitude if disturbed. If three or more annular jets are properly fastened together by a rigid framework, the resulting combination is also stable in pitch and roll, since each jet will seek its own altitude, thus fixing the altitude of the combination. The same effect can be achieved on a single vehicle by dividing the base into compartments by means of downward-exhausting secondary air jets. Each compartment behaves like a weak annular jet superimposed upon the single strong annular jet. It is not yet clear what the best arrangement of secondary nozzles is, nor how strong (and how power-consuming) the secondary jets have to be. Compartmentation is not the only possibility for achieving stability, but it appears to be the most promising means.[11,12]

Directional stability may be provided by means of stabilizing fins similar to those used on conventional aircraft.

R. Stanton-Jones tells of work done on the Saunders-Roe Hovercraft SR-N1, a vehicle that successfully crossed the English Channel:[15]

> The results of our single-jet experiments led us to believe that the stability would be inadequate, so we decided to compartment the cushion. We did not particularly like the idea of using transverse jets along the centerline of the machine and, in any case, the main structural platform buoyant tank was not practically built. Therefore we decided to extend the area of the craft and put an extra peripheral jet all the way around the outside.

A relatively simple theory for a twin-jet system shows that the stability will become small when the distance between the jets is equal to the hover height. Since we are hoping for a hover height of 1-1/2 feet, it was decided to make the distance between the jets about twice this value in order to ensure an adequate margin of stability.

Results of tests by Tinajero and Fresh indicated,[16]

The dynamic and hovering test results of the 7-foot GEM show the existence of a critical speed that similar vehicles would encounter when traversing sine-wave surfaces of various wave lengths and amplitudes.

For frequencies of disturbance lower than the natural frequency of the vehicle in pitch, the machine will follow the surface indulations, but as these values become equal, increased pitch motions is obtained with the possibility of catastrophically large motions, causing collisions with the surface.

For frequencies of disturbance larger than the natural frequency in pitch, the vehicle becomes increasingly unable to respond at all to that surface beneath it and tends to maintain itself in level flight.

The problem of avoiding collision with the surface while flying at the critical speed in pitch can be solved by a suitable control of $\partial M/\partial \alpha$ (stability derivative), fast acceleration to higher speeds, and varying the altitude above the surface. Further study on the aerodynamic response of GEM's flying over uneven surfaces would be required to confirm the findings. This is especially important for over-water operations.

Harvey R. Chaplin concluded that:[17]

A sound quantitative understanding of the stability is thus even more essential to an evaluation of GEM merits than is the case with conventional aircraft. This state of understanding has not yet been reached.

Effect of Planform

The circular planform is optimum for the hovering condition. For an "integrated system," larger length-to-width ratios will give smaller augmentation losses for a given value of propulsive thrust.[5] In vehicles where control is of prime importance, the minimum width may have to be limited in order to obtain the moment arm necessary to achieve response.[10] In other vehicles the maximum over-all width is primarily limited because of transportability requirements.

Tinajero performed an investigation to determine the aerodynamic characteristics of a special planform. The planform was an elliptical section with the major axis modified to pointed ends and the sides tangent to the ellipse. The length-to-width ratio was 2.6.

> The two major requirements in the choice of the planform were: (a) high utilization of the peripheral jet to achieve propulsive thrust with a minimum loss in augmentation and (b) minimization of the negative pressure peaks in the pressure field while cruising. There is also a slight hope for better stability characteristics with this planform.
>
> By proper design of planform in a GEM utilizing an integrated system, the percentage loss in lift is below the percentage gain in propulsive thrust. An integrated system may well meet the propulsive thrust requirements to achieve forward speed and ability to climb an inclined surface.
>
> The static performance may be predicted easily from theoretical equations and empirical efficiency factors.
>
> There is no apparent large effect (that is, loss in augmentation) due to sharp corners in planform.[11]

Selection and Arrangement of Engines

Because of their poor operating efficiency at low speeds, turbojet engines would not be suitable and the choice will be between either a gas turbine or reciprocating engine. Because of the spray anticipated, the engine must be capable of accepting a high concentration of water droplets and be resistant to sea-water corrosion.[18] Engine blading and cooling must be capable of extended operation under conditions of a high level of sand and dust.

Assault and amphibious operations are demanding affairs and take place in rough terrain. Engines must be exceptionally rugged and self-sufficient to be reliable under these circumstances. Self-caring features should be used wherever possible, because maintenance would be strictly limited or postponed completely during actual landing operations.[18]

T. Strand and T. Fujita[19] state that the theory shows the following quantities should be minimized for optimum operation:

1. Volume of flow per fan

2. Shaft angular velocity

3. Fan-blade section drag-to-lift ratio

4. Duct loss coefficient

Strand and Fujita conclude that significant power savings result by using several small fans, thus reducing the volume of flow per fan. This fact can be understood when it is realized that the total cross-sectional inlet area of a multiple-fan arrangement can be larger than that of a lesser number of fans. Thus with a larger total cross-sectional fan area, the axial fan velocity is reduced for the same total volume of flow causing the decrease in the duct losses.

Performance improves as the complexity of the design increases, but the simplest design, a single-fan configuration, requires only 25 percent more power than the best twin-fan configuration.[20]

Choice of Base Pressure

While the base pressure on a GEM is remarkably low, even with a highly loaded vehicle, it is a significant factor in the operation of the vehicle. Base pressures run anywhere from 10 lb/ft^2 to 80 lb/ft^2. Several qualitative remarks can be made:[13]

1. The higher the base pressure the greater the exit velocity and the greater the debris problem. (Exit velocity is proportional to the square root of the base pressures.)

2. The higher the base pressure the greater the surface depression when over water. This may be significant at <u>moderate</u> speeds from a water-resistance viewpoint (the vehicle is continuously running uphill).

3. The higher the base pressure the more compact the vehicle becomes.

4. The higher the base pressure the less favorable the power loading (pounds per horsepower) for a given clearance.

Operating Conditions

After configuration, means of propulsion and control, type and arrangement of engines, planform, and methods of insuring stable operation are decided upon, the general problems encountered in actual operation or anticipated when operating on a larger scale can be considered.

Additional problems are associated with operation over water. Chaplin[17] lists the most important as:

1. Water Surface Depression — At hovering and low forward speeds, the surface under the GEM is depressed. The depth of depression is proportional to the wing loading. For example, a GEM with a loading of 50 lb/ft^2 will depress the surface to an average depth of about 0.8 foot. This amounts to an 0.8-foot loss of "useful" altitude, as measured from the free water surface.

2. Wave Drag — At higher speeds, the depression changes into a slight rearward slope of the surface directly under the GEM. If the GEM is flown parallel to the mean surface under it, its lift vector tilts rearward to produce a "wave drag" component. This drag has not been evaluated for practical GEMS. It appears that it might be appreciable but not prohibitive.

3. Stability Reduction — At hovering and low speeds, there is an appreciable reduction of the stability derivatives because of the yielding of the water surface.

4. Spray Generation — Spray has been a source of some annoyance in model tests and early test vehicles. There is reason to believe that there will be substantially less spray with full-scale practical vehicles, but this remains to be seen.

5. Dynamic Response to Waves — This is, potentially, a serious problem. GEMS have "resonant" frequencies of their pitch, heave, and roll motions, which can be excited by the disturbances caused by passing over waves. There are critical forward speeds, depending on the height of the GEM and the average distance between disturbances. This is being studied by model tests. A great deal of additional research effort will be required to establish practical criteria for what vehicle characteristics, surface conditions, and flight speeds are feasible.

Spray generation is also a facet of the more general problem encountered when operating over loose terrain. Peripheral-jet machines and plenum machines continuously eject a flux of air from their base perimeter. This air is ejected at velocities of 50 to 150 ft/sec or more.[13]

In reporting on the development of the Saunders-Roe Hovercraft SR-N1, R. Stanton-Jones says:[15]

> The main lessons that have been learned during the past three months of trials and demonstrations are that over land the dust created with this type of ground effect machine would be very serious indeed, while on the sea the spray is an equally serious problem, although it is alleviated to a certain extent as the speed of the machine increases and is only likely to be a problem at low forward speeds. However, the cushion loading on the SR-N1 is very low and theoretical studies indicate that cushion loadings of the order of 50 to 100 lb/ft^2 instead of 17 lb/ft^2 are more likely economical values for practical hovercraft. At these conditions the dust and spray would be three or four times as bad as on the N1. For example, during a two-hour operation over the sea we got as much as a quarter of an inch of salt on the cylinders of our engine and after each operation we had to completely wash down the whole machine with fresh water. This is acceptable on a research vehicle, but it would clearly be quite impractical and uneconomical on any sort of operational machine.

Richard E. Kuhn[21] conducted an investigation to determine conditions under which downwash from vertical-take-off-and-landing (VTOL) aircraft will start surface erosion from various types of terrain. He found that the erosion of sand and loose dirt started at dynamic surface pressures of 1 to 3 lb/ft^2, which is in general agreement with helicopter experience. Thoroughly soaking the sand and loose-dirt surfaces increased the resistance to erosion to dynamic surface pressures of 30 to 50 lb/ft^2. Spray from water started at dynamic surface pressures of 1.5 to 2.5 lb/ft^2. Sod withstood dynamic pressures up to about 1000 lb/ft^2.

Even the helicopter, with probably the lightest disk loading and the lowest downwash velocity of VTOL aircraft (2 to 3 lb/ft^2 dynamic pressure), raises considerable dust when operating over loose dirt or dry beach sand. This dust cloud seldom seriously limits operations, but it is definitely a nuisance even for lightly loaded helicopters.

Kuhn concludes in part that the results in general indicate that the onset of erosion depends primarily on the dynamic pressure of the outward flow of air parallel to the surface and is relatively independent of the nozzle or ducted-fan height or exit dynamic pressure which combine to produce the necessary dynamic surface pressure.

Thoroughly soaking the surface with water delayed the onset of erosion to dynamic surface pressures that would be obtained with aircraft supported by propellers or rotors with disk loadings of 30 to 50 lb/ft^2. This experience with wetting the surface suggests that some of the soil-stabilization techniques currently available may be able to provide adequate operating surfaces.

In comparison to helicopters, GEMS operate with higher dynamic pressures. It has been mentioned earlier in this report that ground effect machines eject air at velocities of 50 to 150 ft/sec. The dynamic surface pressure corresponding to these velocities is determined to be 2.9 to 26.3 lb/ft^2 as calculated from

$$P = \frac{V^2}{2g} \gamma$$

where P = the dynamic pressure (lb/ft^2)

V = the exit velocity (ft/sec)

g = the gravitational constant (ft/sec^2)

γ = the density of air (lb/ft^3)

Finally, when using operations research techniques to evaluate GEMS for use as lighters, it is popular to envision them operating at high speed with low clearance height. Jackson and Southcote present these tempering thoughts:[22]

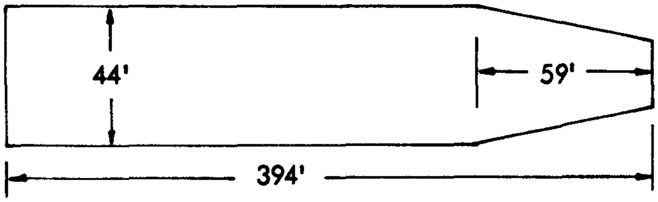
> It is quite possible that this optimum cruise velocity of 80 mph may be extremely difficult to achieve in practice. Reflect for a moment on the control problems associated with this 50-ton vehicle traveling at 80 mph one foot over unimproved terrain. Obstacles that would require more than one foot clearance may be circumvented, and in order to accomplish this an extremely powerful and responsive control system would be required. Even if this were available, it is doubtful if the reactions of the driver would be quick enough, particularly in connection with overland operation. It is conceivable that this speed could be maintained on an inland water system, for example, like the Mississippi River, but in the authors' opinion, highly unlikely in most overland operations.
>
> It is difficult to specify a typical speed limit. Undoubtedly, the limit would depend to a large extent on the driver's ability, and the effectiveness of the control system.

DISCUSSION RELATING TO RECOGNIZED PROBLEM AREAS

Amphibious Support Vehicle

Ground effect machines that are to be used in amphibious support must be transported by ship to the area of operations. Their size will therefore be limited by the maximum-allowable size for ships. GEMS could be carried on the flight deck of aircraft carriers. Carriers have the special requirement that no part of the ship's fixed structure, armament, or installed equipment shall extend outboard more than 126 feet from the centerline of the ship.[23] If the GEM is to be carried in the hull of a ship, it will be limited by the size of the hull (more specifically by the hatch size or well size) which, in turn, is limited by the 110-foot width of the locks of the Panama Canal.[24] Therefore, it can be assumed that the maximum width of a GEM to be carried in this manner will be about 100 feet.

The quantity of transport shipping presently available to carry the Amphibious Support GEM to the operating area narrows considerably when the dimensions of the craft are projected to carry a respectable payload. It might be well to study the availability of LSD's or LPD's and determine the optimum dimensions for the GEM from the standpoint of maximum payload that can be shipped with reasonable efficiency. Shown below are the well-deck dimensions of the Thomaston Class LSD in plan view.[25]



The operating height of a GEM imposes an indirect limitation on its width. How far above the surface will a GEM have to operate in order to assure a better-than-60-knot cruising speed over water with sea conditions in which present-day craft can and do operate? Landing craft operating in the open sea and making ship-to-shore transit rarely can withstand sea states greater than 3, i.e., 3- to 4-foot waves (trough to crest), 10- to 15-knot winds, and a 6-foot plunging surf. Amphibious operations are carefully planned; based on long-range forecasts, they are usually carried out under much more favorable conditions. The ideal situation therefore would be to have a vehicle with a 2-foot cruising height just barely skimming over the tops of the waves on the way to shore and a trade-off in power to enable the machine to slow up and cruise at a higher height to get through the surf.[25]

Chaplin[20] in his design study of a 20-foot GEM says the minimum dimension of the base was determined from the requirement that the machine be stable at a hover height, h, of 3 feet. It was estimated that the minimum dimension of the base should be not less than 25 feet, in order to have a reasonable assurance of meeting this requirement. This agrees favorably with the generally accepted limitation that cruising heights of the order of 2-5 percent of the effective diameter appear presently reasonable, with maximum hover height at 10-12 percent of the diameter. That it does not agree entirely may be largely due to terminology.

The term "effective diameter" is often used in conjunction with ground effect machines whose planform is not a circle. The effective diameter of a non-circular planform is the diameter of a circular planform that would have the same ratio of exit-to-plan area when operating at the same height. It can be shown that for a rectangular planform the effective diameter is

$$D_{eff} = \frac{2nW}{n + 1}$$

where W = the width

n = the ratio of length to width

The effective diameter will be between 1 and 2 times the minimum dimension, but the limitations above were established with vehicles having effective diameters very nearly equal to the width, and it will be assumed here that Chaplin has stated the more valid limitation.

If the vehicle is to operate over water with a sea state of 3, the maximum hover height should be at least 4 feet. Due to the water depression this will correspond to a greater hover height over land. It might be assumed that the water depression is 1 foot — the exact value will be determined later. If the hover height should not exceed 12 percent of the minimum dimension of the base, this dimension will be 41.2 feet for stable operation at a hover height (including water depression) of 5 feet. Thus the minimum width, determined by the operating condition, and the maximum, determined by the space limitations on LSD's are approximately the same.

The length-to-width ratio of the ground effect machine will be determined by operating conditions. For hovering, an aspect ratio of 1:1 is optimum. Larger length-to-width ratios will give smaller augmentation losses for a given value of propulsive thrust,[12] but extreme ratios have some definite disadvantages in designing for roll stability.[11] A length-to-width ratio between 2:1 and 3:1 can be taken as a practical maximum.

Analysis of a specific over-water vehicle within these general conditions may clarify this discussion. A base pressure of 72 lb/ft^2 will be used. This is on the high side of pressures that have been used — 20 to 80 lb/ft^2 — but well within the limitation of under 200 lb/ft^2.[12]

Dimensions chosen:

Width	= 42 ft
Length	= 105 ft
Plan area	= 4410 ft^2
Base pressure	= 72 lb/ft^2
Gross capacity	= 317,520 lb
Maximum hover height over water	= 4 ft

Because there will be some leveling of the water surface, it is difficult to assess the effect of water depression on operating height. In the absence of more specific information it seems best to add the water depression to the desired operating height over water. In this case the average water depression is 1.15 ft (72/62.4), assuming fresh water.

Chaplin[5] expresses hovering performance by a dimensionless figure of merit which provides a direct indication of the important lift-to-power ratio, L/P, and a direct comparison with the ideal shrouded propeller or helicopter. The figure of merit is

$$M = \frac{1}{2\sqrt{\rho}}\frac{L}{P_c}\sqrt{\frac{L}{S}} = \frac{L}{2P_c}\sqrt{\frac{L}{S\rho}}$$

where L = the total lift (lb)

P_c = the cushion-system power (lb-ft/sec)

ρ = the mass density of air ($slugs/ft^3$)

S = the base area (ft^2)

The optimum figure of merit will be equal to the size-to-height ratio S/hC. Practical design limitations, internal losses, etc., will limit actual vehicles to

$$M = \frac{0.6S}{hC}$$

where h = the operating height (ft)

C = the perimeter of the base (ft)

Equating the above, the horsepower required for hovering (HP_c) is determined to be

$$HP_c = \frac{P_c}{550} = \frac{hC}{660\sqrt{\rho}}\left(\frac{L}{S}\right)^{3/2}$$

For the vehicle chosen, this has a numerical value of 27,900 horsepower ($L/S = 72$; $h = 5$).

When the vehicle moves horizontally in forward flight, a ram drag equal to the air-mass-flow rate through the peripheral nozzle times the forward velocity occurs. Also, the required pressure rise for the cushion power is reduced by the amount of the free-stream dynamic pressure recovered by the inlet.[5]

The cruise performance is expressed by the dimensionless "equivalent lift-to-drag ratio" LV_o/P where P is the cushion-system power plus propulsion-system power in ft-lb/sec, and V_o is the free-stream velocity in ft/sec. The optimum value of the lift-to-drag ratio is

$$2\frac{S}{hC}\ \frac{v}{\sqrt{1 + v^2}}$$

where v = the dimensionless velocity parameter $V_o/\sqrt{L/\rho S}$

Actual vehicles of the simple air-curtain type will probably be limited to equivalent lift-to-drag ratios of about $0.7S/hC$ at optimum cruise speeds corresponding roughly to $v = 1.0$.

For the sample vehicle the optimum cruise speed is 174 ft/sec (118 mph). For the fully loaded vehicle, horsepower requirements are given for various speeds and heights.

Horsepower Requirements

Operating Height (ft)	118 mph	90 mph	60 mph	30 mph
1.250	14,350	13,600	12,380	12,650
1.875	18,250	16,600	16,900	16,900
2.500	25,100	25,400	25,400	25,380

It should be noted that the amount of air that must be supplied to maintain lift decreases with increasing speed, while the power to overcome drag increases. Therefore, the total power required as the speed increases is not greatly altered from the value while hovering.

The payload that the vehicle can carry is determined by the range, the operating speed, and the operating height. The total weight, which is equal to the lift, is composed of the empty weight of the vehicle, the weight of the fuel, and the payload. The empty weight of the vehicle is estimated to be:

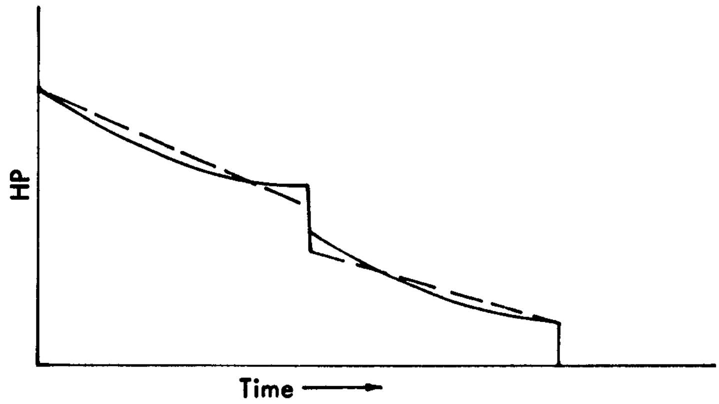
Weight of engines and accessories at 1 lb/HP	=	27,900
Weight of fans shafting and ducting at 1 lb/HP	=	27,900
Weight of structure at 10 lb/ft^2 of plan area	=	44,100
Weight of fuel tanks for 50,000 lb at 0.043 lb/lb	=	2,150
Crew, emergency equipment, supplies, and miscellaneous	=	2,000
TOTAL		104,050 lb

Although the above estimates of weight for the GEM are higher than some, it implies that the vehicle can carry fuel and payload amounting to twice the empty weight.

Solution for the fuel requirements of a mission is not readily obtained since the power requirement is determined by the weight which in turn is inversely proportional to the fuel consumed.

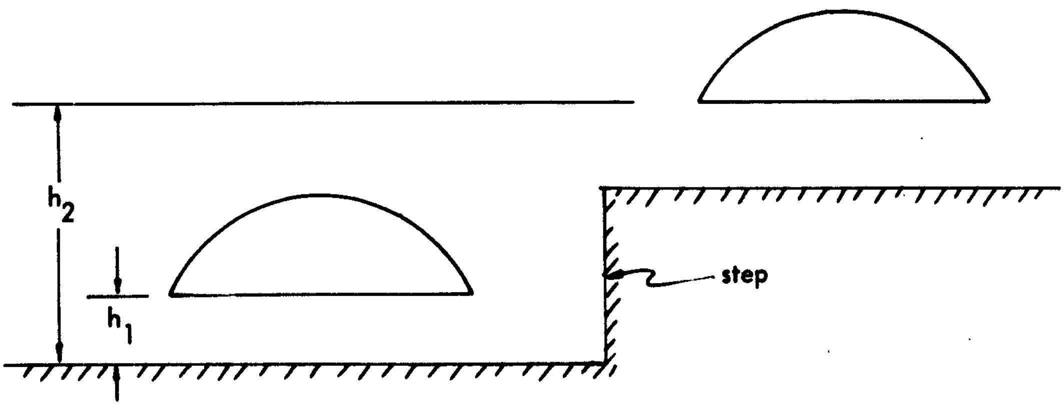
Specific fuel consumption is taken as 0.6 lb/HP/hour. The maximum range for this sample, over-water operation will be considered to be 130 miles each way. The fuel consumption then is determined from the product of the area under the horsepower-versus-time curve and the specific fuel consumption. Fuel required for a 260-mile trip at a 2.5-foot height is: 63,800 pounds at 60 mph, or 28,900 pounds at 90 mph.

A 149,670-pound payload can be carried when operating at 60 mph; at 90 mph this is increased to 184,570 pounds. The payload weight must be equally distributed, or the resulting tilt will reduce the effective operating height and cause an unwanted thrust or drag force.



As indicated by the solid line on the above curve, the equation for the required horsepower is not linear, but will be considered as such (dotted line). The discontinuity in the curve is due to the sharp reduction in horsepower requirements after unloading at the destination and starting the empty return trip.

The question of how well a ground effect machine of this size will respond to a rapid change in operating height remains to be answered. This "step climbing" occurs when crossing surf or terraces. The vehicle may be stable at h_1 and at h_2, but consider the consequences when the vehicle is centered over the step. Does the dumping of air cause the GEM to tip over backwards? How can this be corrected? The application of additional thrust other than the ground cushion or an initial nose-down inclination and dependence upon the inertia of the vehicle are possible solutions.



While the GEM is operating, the exit velocity will be

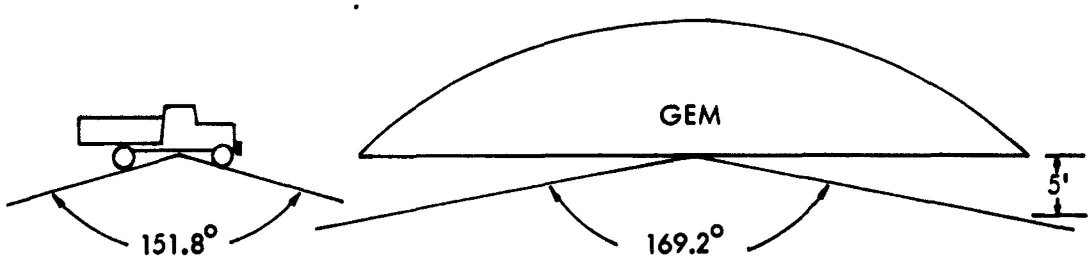
$$V_j = \frac{550HP}{0.6PhC}$$

$$V_j = \frac{550\,(25,400)}{0.6\,(72)\,2.5\,(294)}$$

$$V_j = 440 \text{ ft/sec or } 300 \text{ mph}$$

This is sufficiently high to start surface erosion of wet sand and is much higher than the dynamic pressure causing erosion of dry sand or water. Obviously, no ground personnel can be expected to work close to a device creating a 300-mph wind. The debris and wind disturbances caused by a GEM operating over the beach could effectively incapacitate, temporarily, any friendly troops within close range. Work is underway to develop protection for the machine, but more thought should be given to improving the protection of personnel and to determining the range of the disturbance.

A 5-foot clearance height is impressive after dealing with vehicles that have only a 6- to 9-inch ground clearance. However, on undulating terrain, comparison of the 105-foot GEM and a 2-1/2-ton truck with its relatively short wheelbase shows that the truck can tolerate a more rapid rate of change in topography. This is shown in the following sketch which illustrates the fact that the truck can negotiate intersecting planes with an angle of 151.8 degrees; whereas the GEM, with a 5-foot clearance, because of its much greater length, can only negotiate less-abrupt intersecting planes with an angle of 169.2 degrees.



Since the amphibious vehicle is for military use it is desirable to examine the strictly military attributes of the ground effect machine. The GEM cannot be designed with the ability to bulldoze or carry armor plate without a great loss in the payload. GEMS do have the advantage of high speed, but when this factor is considered in respect to their necessarily large size it often becomes less effective defensively. For example, a 105-foot GEM traveling at 35 mph will take longer to pass a fixed-point-of-fire than a 20-foot truck traveling at 10 mph. If this comparison were considering only small-arms fire, with the vehicle operator as the target, then the GEM would be favored. However, if the comparison considers light artillery, where a hit any place on the vehicle would immobilize it, then the truck would have the advantage.

In addition to the irritation to ground personnel, the dust cloud created by the GEM would be a definite guide to its location.

Quiet operation does not seem compatible with the air flow envisioned.

Because it is not restricted to roads or waterways, the general traffic pattern of incoming GEMS will be hard to determine.

Ground effect machines, because of their large size and uncertain control, could not be considered agile enough to maneuver around objects. In addition, defenses against GEMS would be simple. Stout posts spaced 30 feet apart and only 6 feet high would stop any GEM between 31 and 49 feet wide. A similar ratio of heights and spacing could be used to retard any other size GEM. Wooded areas would of course preclude GEMS.

The end result of some of the past studies on ground effect machines has been an operations research to compare them economically with more conventional means of transport. R. Stanton-Jones[26] points out that in determining direct-operating costs there are so many arguable assumptions, such as cost of manufacture, type of fuel, efficiency of operation, utilization, and so on, that it is possible (by "suitable adjustment") to make the direct-operating-cost figure equal any desired value. In fact, it is doubtful if direct-operating costs can mean anything at all until commercial GEM vehicles have actually operated, and even then costs will be influenced by many other factors.

In summarizing the applicability of ground effect machines for amphibious support:

1. They are independent of the surface to a greater extent than any conventional surface vehicle and are capable of high-speed operations.

2. They are only practical in the larger sizes.

3. Fuel consumption is high.

4. Operations will be accompanied by objectionable noise and debris.

5. Serious problems of control and stability must be solved.

Polar–Personnel and Freight Carriers

In polar regions, operations mobility has been greatly limited by conditions of snow, tundra, and water. Snow can support loads with bearing pressures of only about 400 to 700 lb/ft^2. Snow is temporary and in some locations is criss-crossed with deep crevasses and pressure ridges which are difficult to detect from a moving vehicle and are hazardous to wheeled or tracked vehicles. When the snow melts, a vehicle that operated efficiently over snow, such as a sled, is immobilized.

GEMS, operating as they do without direct contact with the ground, would be freed of some of these problems.

The occasional impact with the surface or waves when operating over open water could not be tolerated when operating over ice. It is therefore necessary that the clearance height be accurately maintained. Operations over water in freezing weather would be difficult; the ingestion of water could cause icing of the propellers and driving mechanism.

The vehicle signature and the effects of the air blast are more pronounced due to the reduced mass density of snow. Encounters with ground personnel would probably not be so frequent, and snow clouds would be less hazardous than blowing sand.

Fuel costs are increased in polar regions, because of inaccessibility, and this should be considered in an economic study.

As mentioned previously, a ground effect machine with sufficient load-carrying capacity to be practical would be too large to operate in forests, and forests are common to sub-polar regions.

The ram wing, which by itself is not suitable as a ground effect machine, originated as a variation of the air sled and should be considered further for use over snow.

In cold regions, an adaptation of ground effect machines could be feasible. Such a vehicle might be an amphibious sled with the ground effect contributing to reduced ground pressure. The runners could be constructed as an integral part of the vehicle, and captured air could serve as flotation chambers. Over solid terrain the rear air bag (Rolligon or Terra Tire type) could be hydraulically lowered and locked into position. Two wheels in front could serve as both drive and steering wheels with sufficient penetration in more resistant soils to supply the full driving power.

Shoreline Construction

One of the most surprising applications of the GEM may be in the construction and repair of naval facilities. GEMS offer the advantage of high-speed operations over mixed terrain. The large size that is required for acceptable operating heights within a reasonable h:D ratio becomes a distinct advantage. With adequate buoyancy incorporated, the GEM offers a large, stable, floating, work platform that can rapidly change position. Typical operations might include:

1. Sounding and marking the channel in an inlet
2. Rapidly ferrying large repair parts from a supply ship to inland construction sites, e.g., transporting a dozer blade to an airfield
3. Unfouling lines and aiding boats that have run aground
4. Carrying facilities for repairs of a more specialized nature
5. Serving as a general service vehicle, land-based, in the center of an amphibious operation
6. Serving as a diving or pile-driving platform
7. Transporting personnel

Special requirements would be:

1. Minimum of obstructions on flat deck
2. Provisions for power take-off for winches, etc.
3. Means (such as an outboard motor unit) for manipulation in the water

CONCLUSIONS

1. Ground effect machines have limited application in the field of polar transport, amphibious support, and shoreline construction. The increase in mobility and operating speed offered by GEMS can only be attained by the use of large vehicles which necessarily have high rates of fuel consumption. On the basis of predicted performance, GEMS appear to be limited to carrying high-priority cargo.

2. At present there is no GEM capable of stable operation at heights greater than 2 feet.

3. Problems of stability and control limit operating heights of 0.1 of the effective diameter.

4. The noise and debris resulting from the air blast of the plenum-chamber and peripheral-jet ground effect machines are serious handicaps. The development of other configurations is not extensive enough to permit evaluation.

RECOMMENDATIONS

1. Since this study indicates that current ground effect machines have only very limited application within the field of responsibility of the Bureau of Yards and Docks, it is not recommended that the Bureau actively pursue the development of such vehicles at this time.

2. Since other government agencies are actively engaged in development of ground effect machines, it is recommended that specific criteria be established for the requirements of the Bureau of Yards and Docks in this field, and that these criteria then be submitted to those agencies for possible inclusion in their development programs.

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LIST OF SYMBOLS

A = Effective area of discharge

C = Discharge coefficient or perimeter of base

D = Diameter

g = Gravitational constant

h = Clearance or hover height

$h{:}D$ = Clearance- (or hover-) height-to-diameter ratio

L = Lift (lb)

M = Figure of merit

n = Ratio of length to width for a rectangular planform

P = Pressure

P_c = Cushion system power (lb-ft/sec)

S = Base or cushion area (planform)

V = Velocity

V_j = Exit velocity (ft/sec)

V_o = Free-stream velocity (ft/sec)

W = Weight or width

γ = Density of air (lb/ft^3)

ρ = Density of air ($slugs/ft^3$)

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